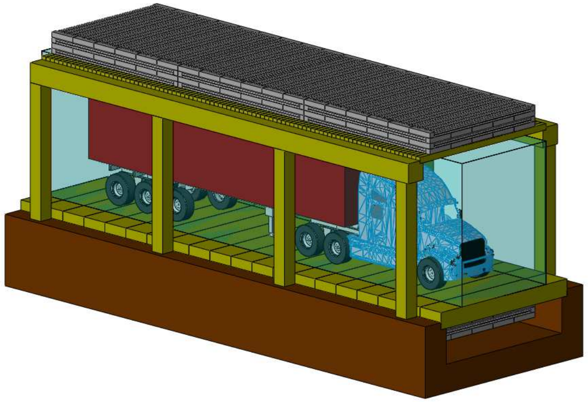
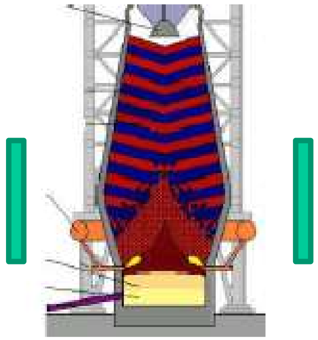
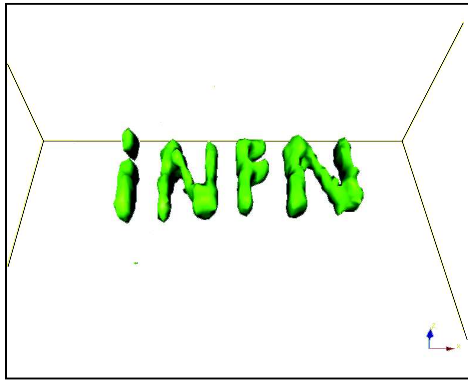
Review of possible applications of cosmic muon tomography*







* Talk with the support of INFN_E

Outline

- **Introduction**
  - ⇒ Historical overview
  - ⇒ Basic Principle of muon tomography
- **Reconstruction techniques**
  - ⇒ Basic (POCA)
  - ⇒ Tomographic (MLEM)
- **Experimental setup**
  - ⇒ The detectors
  - ⇒ An example
- **Applications**
- **Final remarks**

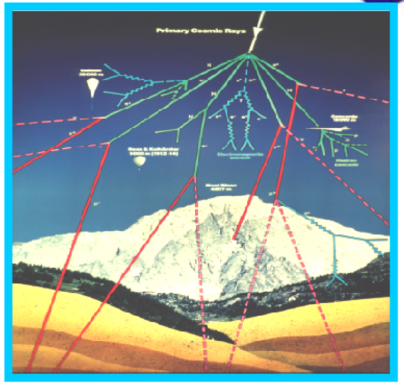
Introduction

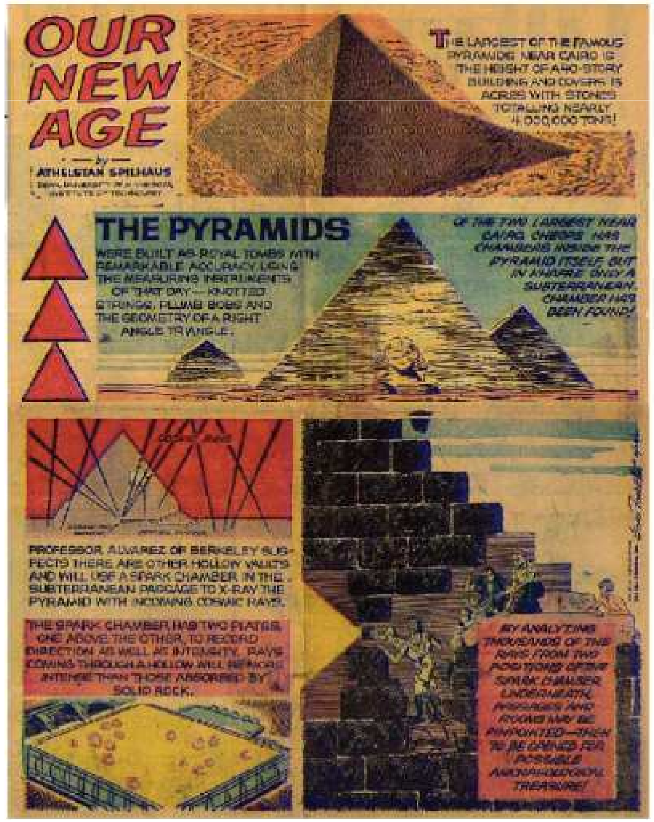
Historical Overview

- Cosmic muons can be treated as ordinary x-rays in usual radiography by looking at their absorption
- The first application of cosmic muons was obtained in 1955 by E.P. George to determine the depth of rock above an underground tunnel **E.P. George Commonwealth Engineer 1955,455**
- A spectacular application was obtained by Nobel Prize L.W. Alvarez inspecting the Chefren pyramid to search for hollow vaults

  L.W. Alvarez et al. Science 167 (1970), 832
- More recently volcanoes inspection was performed

  K. Nagamine et al. N.I.M. A 356 (1995), 585. +…..





Introduction

Basic Principle of cosmic muon tomography (CMT)*

A completely different approach: Multiple Coulomb Scattering (MCS)

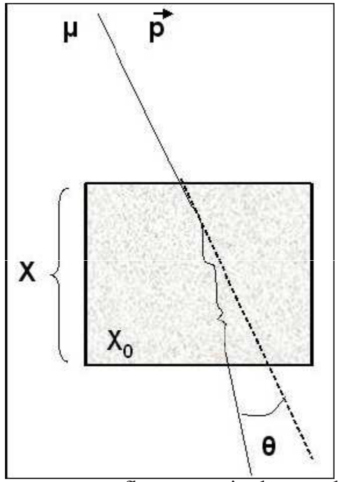
- **Charged particles crossing material are deflected (and decelerated)**
- **The deviation angle (projected on a plane) has a ~gaussian distribution with mean 0 and r.m.s. which depends on:**

$$\sigma \approx \frac{13.6MeV}{pc}\sqrt{\frac{X}{X_0}}$$

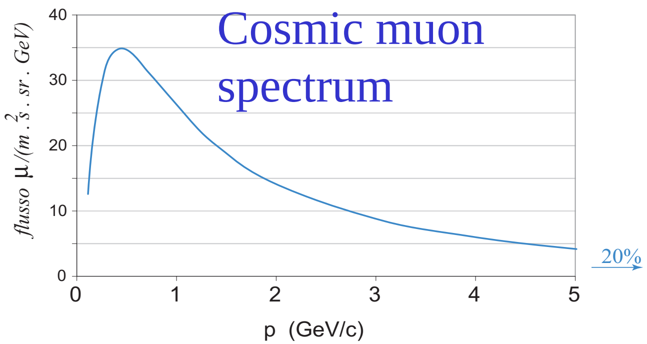
- inverse of muon momentum p
- material thickness X
- radiation length X_0 (~1/Z) **or**

Linear Scattering Density $\lambda = 1/X_0$

- **The momentum of an individual particle p_i is in general unknown**
- **It can be substituted by a fixed value computed from from <1/p²>**



flusso verticale μ s.l.m.



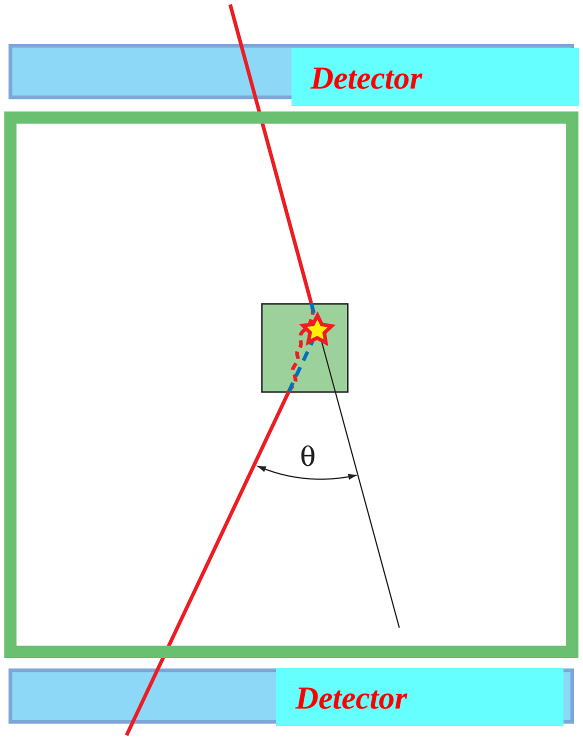
* Los Alamos group K. R. Borozdin et al., Nature 422 (2003) 277. +….

Reconstruction Techniques

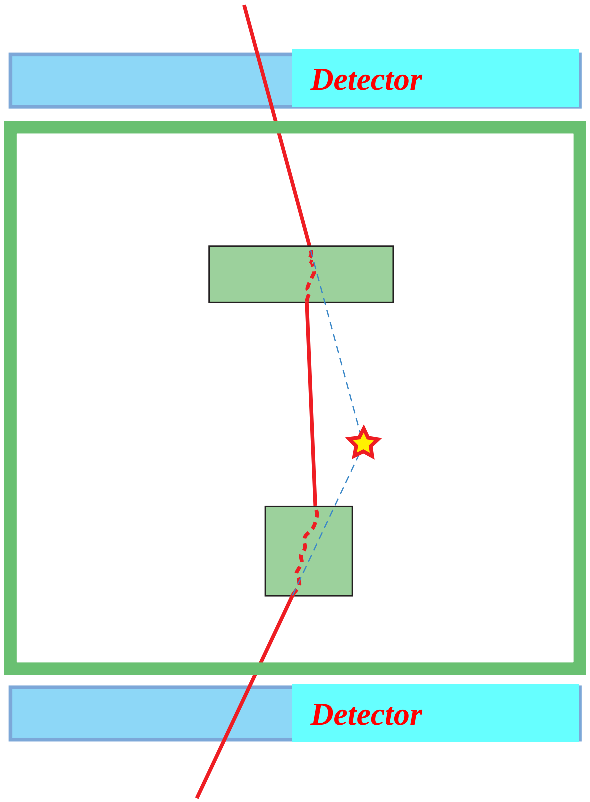
Two detectors to measure position and direction of the muon: in and out

Basic (POCA)

- **Simplest method: Single Scattering Approximation (SSA). In space: Point Of Closest Approach (POCA) of 2 straight lines with a weight $w=\theta^2$**

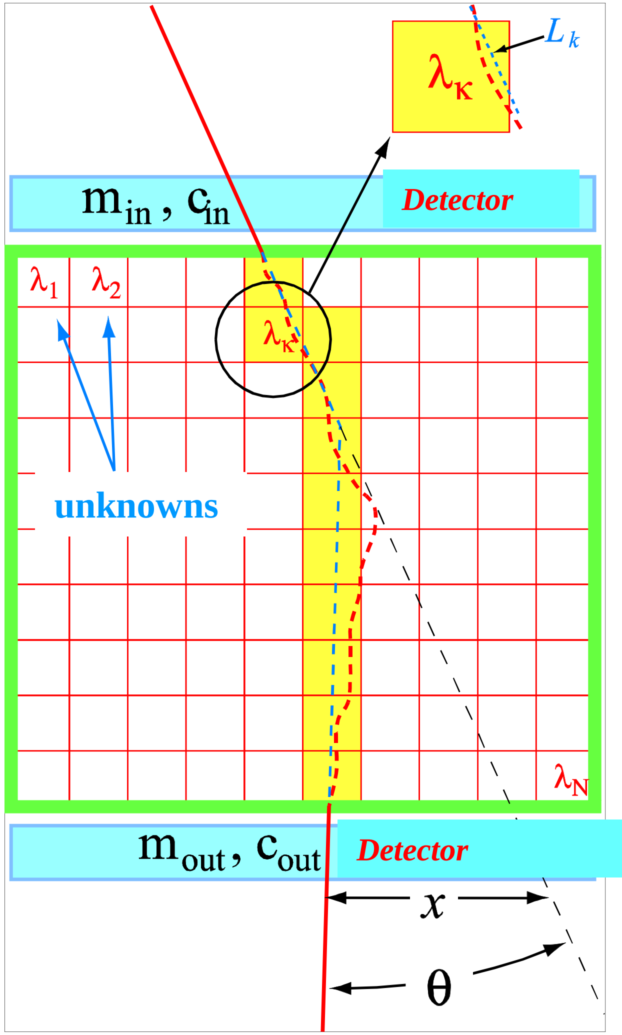


- **It tends to fail in presence of several scattering centers**



Reconstruction Techniques

Tomographic (Maximum Likelihood Expectation Maximization)*



Define **linear scattering density LSD** for a material: $\lambda = 1/X_0$

the average square deviation expected for a particle i crossing L

$$\sigma_i^2 \approx \left(\frac{13.6 MeV}{p_i c}\right)^2 L\lambda$$

If the material is not homogeneous the volume can be divided into N cubic voxels and $L\lambda \rightarrow \sum_k L_{ik}\lambda_k$

where $\{\lambda_k ; k=1,\ldots N\}$ are N unknowns

with $\{s_i^2 = \Delta\theta_i^2 ; i=1,\ldots M\}$ M measurements.

given the Gaussian p.d.f. $$P_i = P(s_i \mid \sigma_i) = \frac{1}{\sigma_i\sqrt{2\pi}} e^{-\frac{s_i^2}{2\sigma_i^2}}$$

with an iterative optimization algorithm (MLEM) applied to a Maximum Log-likelihood functional the system can reach reasonably approximate values of λ_k

* Other algorithms: see ref. list

Detectors for MCS tomography

Requirements

- Large areas $\Rightarrow$ reliable and cost effective instruments
- Good tracking performance
- Good angular resolution: $\Delta\theta < O(10\ \text{mrad})$
- 2x 2D measurements (at least one good for $\Delta\theta$ measurements)
- Stability in time and position

and also (if possible)

- Momentum ~measurement

  $\Rightarrow$ time precision for t.o.f. evaluation

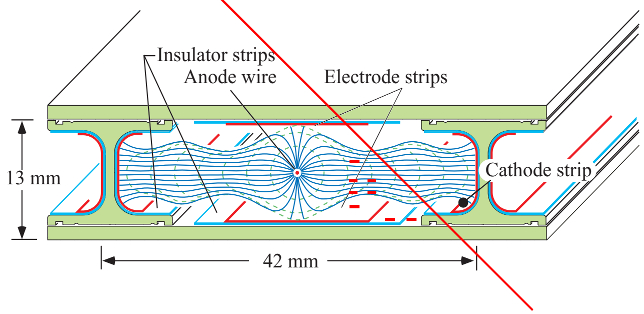
  or

  $\Rightarrow$ high redundancy for self MCS measurements or….

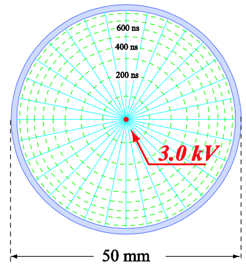
Detectors

Possible solutions

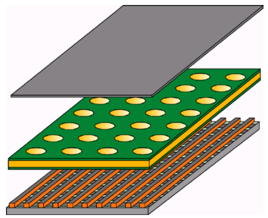
Drift cell



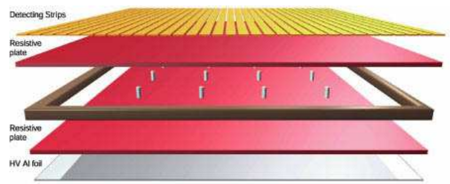
Drift tubes



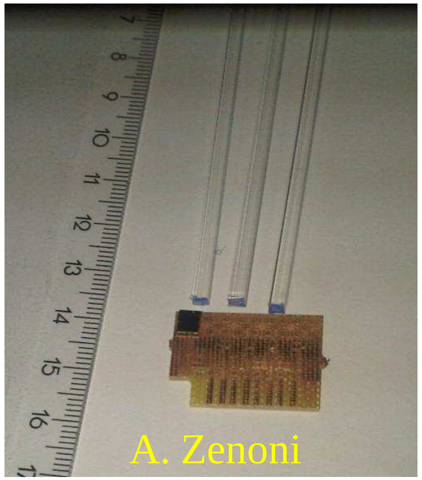
GEM



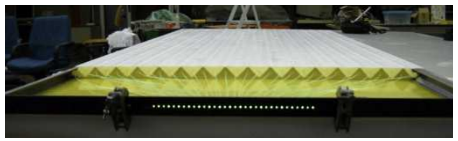
RPC*



Scint. Fibers+SiPM*



Scint.+ WLS Fibers+SiPM*



….and also nuclear emulsions

***Possible precise t measurement: For~ 5 m distance 100 ps time of flight resolution⇒ p< 900 MeV**

INFN
Istituto Nazionale
di Fisica Nucleare
Sezione di Padova

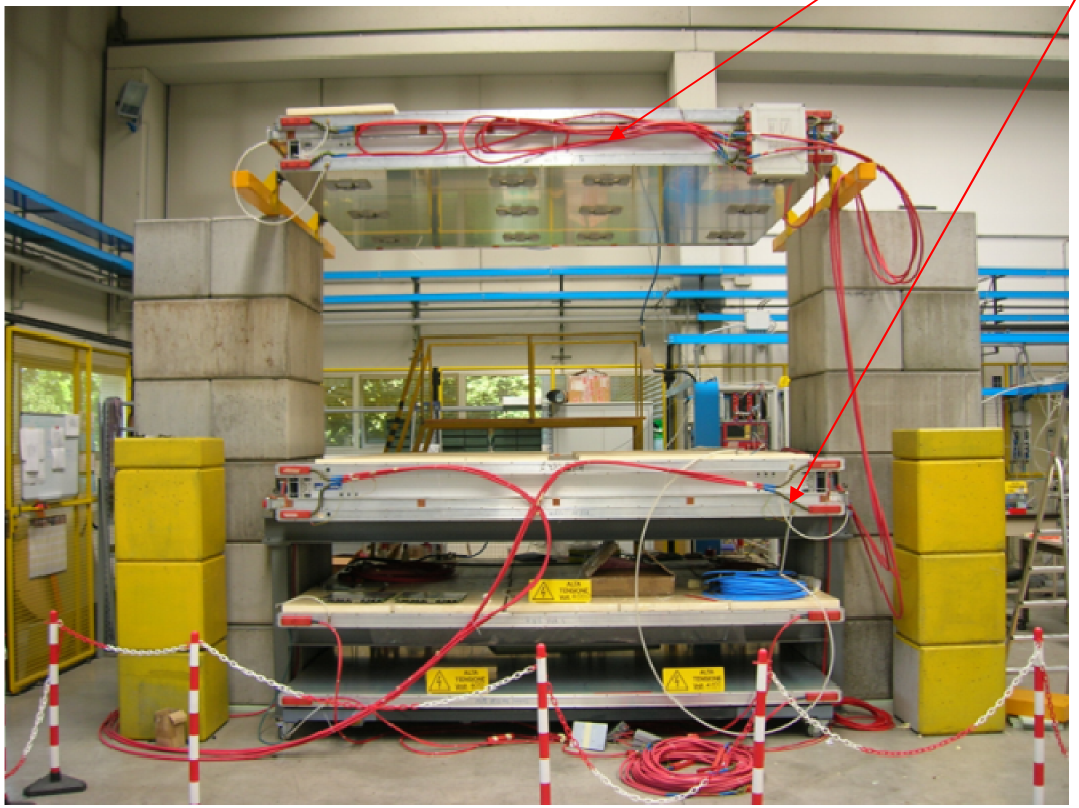
An experimental setup for MCS tomography

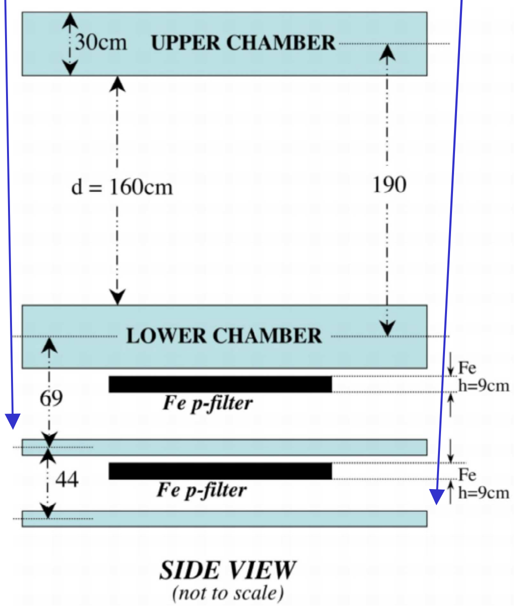
At the INFN National Laboratory of Legnaro (Padova) a demonstrator for the study of muon radiography has been assembled using two spare Muon Chambers Detectors produced for CMS and installed in the barrel

- **Two Drift Chambers 2.5x3.0 m^2**
- **Gap between chambers: 160 cm**

vol. ≈ 11.5 m^3

- **2 extra planes to measure p;**
- **Fe p-filter**
- **Trigger: upper chamber (events "pointing" from upper to lower chamber)**
- **Acquisition rate: 350 Hz**





Cosmic Muon Applications

INFN Istituto Nazionale di Fisica Nucleare

INFN Istituto Nazionale di Fisica Nucleare Sezione di Padova

Possible ambiguity muon tomography/radiography… nevertheless

HEP 65 records found 1 - 25 jump to record: 1

1. Methods and simulations of muon tomography and reconstruction
Henry Fredrick Schreiner III (Texas U.). May 5, 2016.
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
Link to Fulltext; Link to Fulltext
Detailed record

2. The Study of Cosmic Ray Tomography Using Multiple Scattering of Muons fc
Xiao-Dong Wang, Kai-Xuan Ye, Yu-Lei Li, Wen Luo, Hui-Yin Wu, He-Run Yang, Guo-Xiang Chen, Zhi-
e-Print: arXiv:1608.01160 [physics.ins-det] | PDF
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service
Detailed record

3. Discrimination of high-Z materials in concrete-filled containers using muon s
L. Frazão, J. Velthuis, C. Thomay, C. Steer. 2016.
Published in JINST 11 (2016) no.07, P07020
DOI: 10.1088/1748-0221/11/07/P07020
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
Detailed record

4. Advanced applications of cosmic-ray muon radiography
John Oliver Perry (New Mexico U.). Jul 2013. 229 pp.
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
Link to Fulltext; Link to Fulltext
Detailed record

5. Studies on muon tomography for archaeological internal str
H. Gómez, C. Carloganu, D. Gibert, J. Jacquemier, Y. Karyotakis, J. Marte
Published in J.Phys.Conf.Ser. 718 (2016) no.5, 052016
DOI: 10.1088/1742-6596/718/5/052016
Conference: C15-09-07 Proceedings
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
Link to Fulltext
Detailed record

6. The Muon Portal Project: A large-area tracking detector for muon tomograp

HEP 42 records found 1 - 25 jump to record: 1

1. High efficiency gaseous tracking detector for cosmic muon radiography
Dezső Varga (Wigner RCP, Budapest), Gábor Nyitrai (Budapest, Tech. U.), Gergő Hamar (Wigner R
László Oláh (Wigner RCP, Budapest & Eotvos U.). Jul 28, 2016. 15 pp.
e-Print: arXiv:1607.08494 [physics.ins-det] | PDF
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service
Detailed record

2. Advanced applications of cosmic-ray muon radiography
John Oliver Perry (New Mexico U.). Jul 2013. 229 pp.
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
Link to Fulltext; Link to Fulltext
Detailed record

3. Muon dynamic radiography of density changes induced by hydrothermal
Guadeloupe volcano
Kevin Jourde, Dominique Gibert, Jacques Marte Jean de Bremond d'Ars, Jean-Christophe Kon
e-Print: arXiv:1606.03003 [physics.geo-
References | BibTeX | La Harvmac | EndNote
ADS Abstract Servi
Detailed record

4. Co phy of spent nuclear fuel in dry stor
L. Morris, J.D. Bacon, K. Plaud-Ramos, D. Morley, A.
ysics.ins-det] | PDF
BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
stract Service
ed record

5. Development of Nuclear Emulsion Detector for Muon Radiography
A. Nishio, K. Morishima, K. Kuwabara, M. Nakamura. 2015. 4 pp.
Published in Phys.Procedia 80 (2015) 74-77
DOI: 10.1016/j.phpro.2015.11.084
Conference: C14-09-15.7 Proceedings
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote

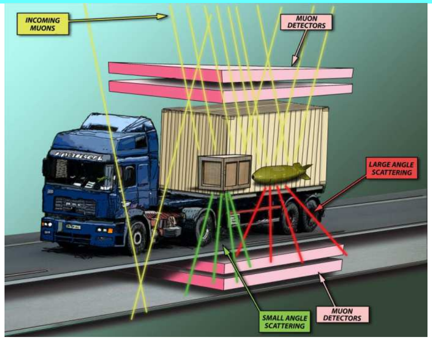
A lot of activity.
Literature is getting relevant

INFN Istituto Nazionale di Fisica Nucleare Sezione di Padova

Cosmic Muon Applications

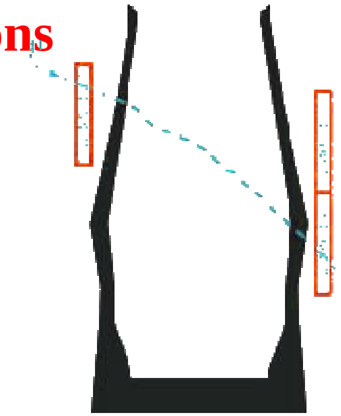
INFN Istituto Nazionale di Fisica Nucleare Sezione di Padova

- **Transport control**

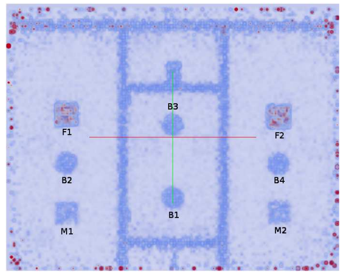


- **Geological survey (vulcanos, mines, CO_2 repositories)**
- **Archeological inspections**
- **Survey of Nuclear Plants (Fukushima)**

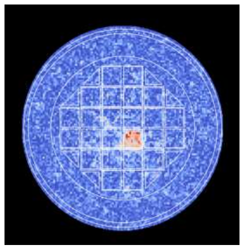
- **Industrial applications**



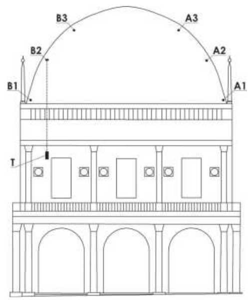
- **LSD precision measurements**



- **Nuclear waste/spent nuclear fuel control**



- **Monitoring of building stability**



INFN
Istituto Nazionale
di Fisica Nucleare
Sezione di Padova

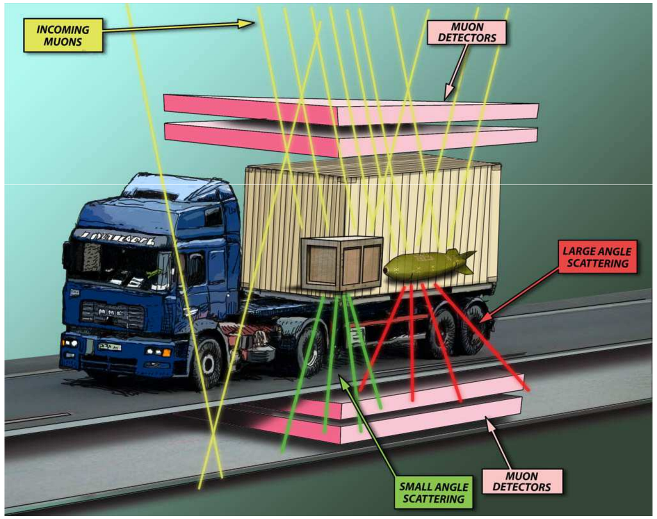
Cosmic Muon Tomography in transport control

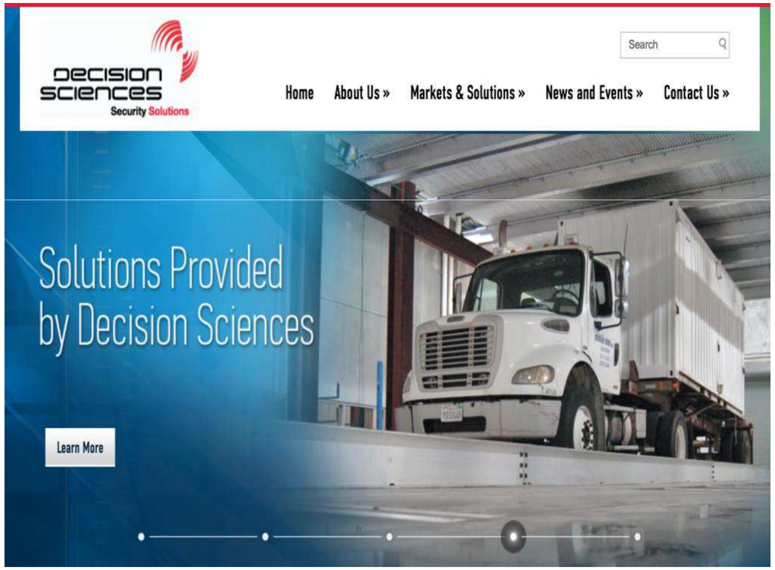
INFN
Istituto Nazionale
di Fisica Nucleare
Sezione di Padova

The 1st application proposed from LA group to use the MCS tomography:

Two detectors positioned above and below the volume under investigation to evaluate the deviation angle of muons.

To detect heavy metals (nuclear contraband)





Requirements of Muon Tomography:
- **large area tracking device**
- **good angular resolution (≤ 10 mrad)**

A portal based on drift tube technology is in operation in Freeport (Bahamas)
Other portals (Catania-Italy) under construction

MU-STEEL

Research Fund for Coal & Steel

Project Title: MU-STEEL - Muons scanner to detect radioactive sources hidden in scrap metal containers

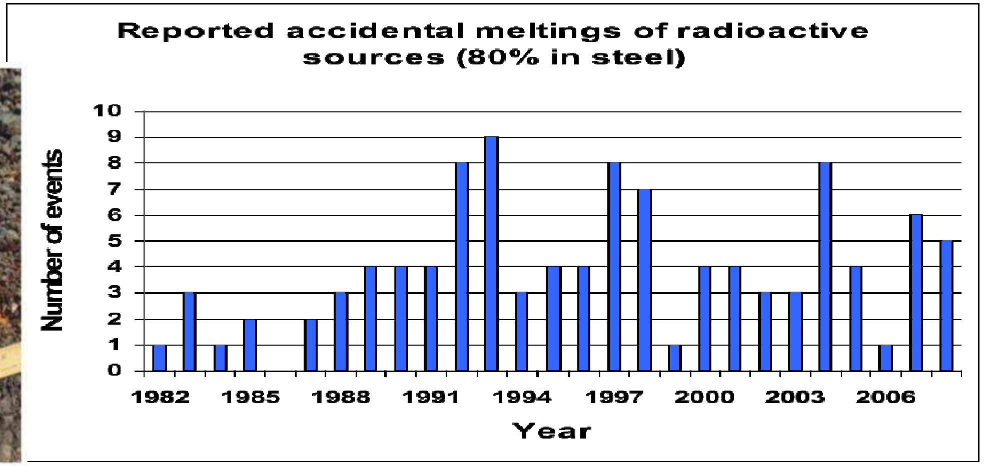
Project carried out with a grant of the European Commission within the Research Fund for Coal and Steel

CMT in transport control/Industrial application

INFN
Istituto Nazionale di Fisica Nucleare
Sezione di Padova

The problem: orphan sources in scrap metal

- **All over the world, radioactive sources are sometimes present in scrap metal used for steel recycling.**
- **In some cases, when the radiation source is well shielded by its heavy metal transportation cask and by the scrap metal itself, it is not detected by radiation portals and is melt, with serious consequences for the plant and public.**
- **MuSteel project: study and design a portal capable to detect the heavy metal shield of the radiation source. NB: in a short (~ 5 min) time**
- **In conjunction with radiation detectors, this system will be capable to intercept every source**



tecnogamma

Università di Brescia - Dipartimento di Ingegne

Università di Padova – Dipartimento di Fisica

INFN

Istituto Nazionale Fisica Nazionale, Padova

GRUPPO AFV BELTRAME

SRB Costruzioni http://www.srb

Project Title: MU-STEEL - Muons scanner to detect radioactive sources hidden in scrap metal containers

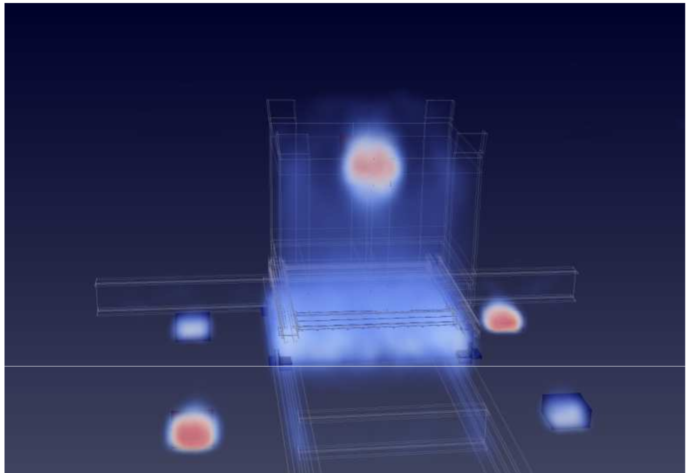
Project carried out with a grant of the European Commission within the Research Fund for Coal and Steel

Cosmic Muon Tomography in transport control

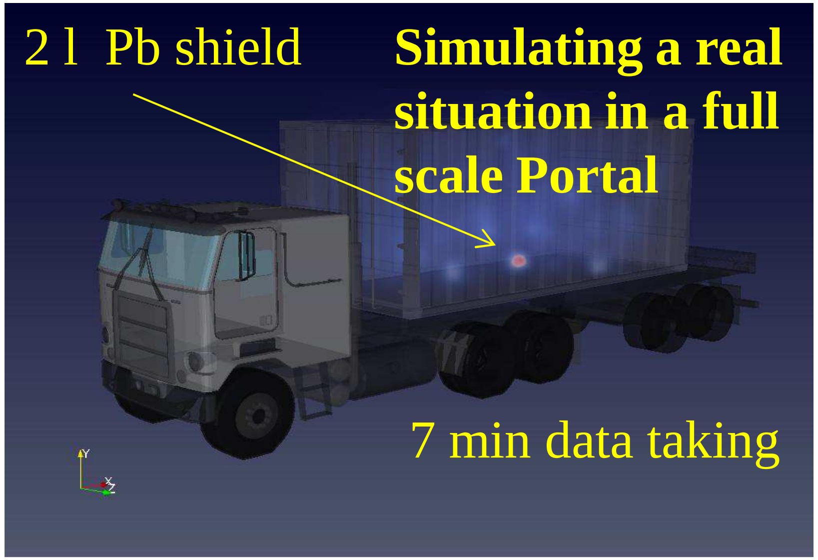
Istituto Nazionale di Fisica Nucleare Sezione di Padova

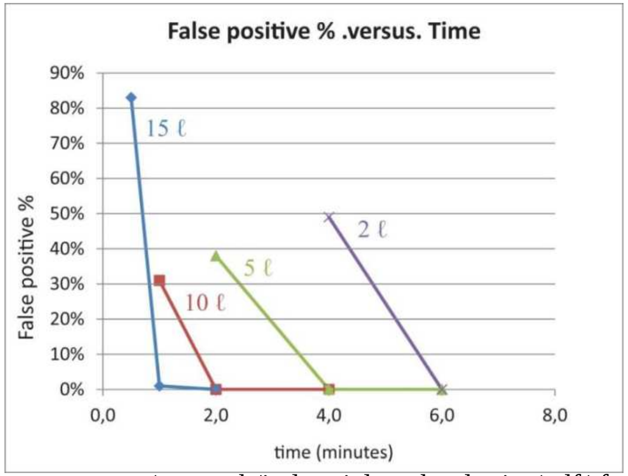
Results:the program was successfully completed:

Reproducing a similar situation in the Demonstrator



M. Benettoni et al *2013 JINST* ***8 P12007 [arXiv:1307.6093].***

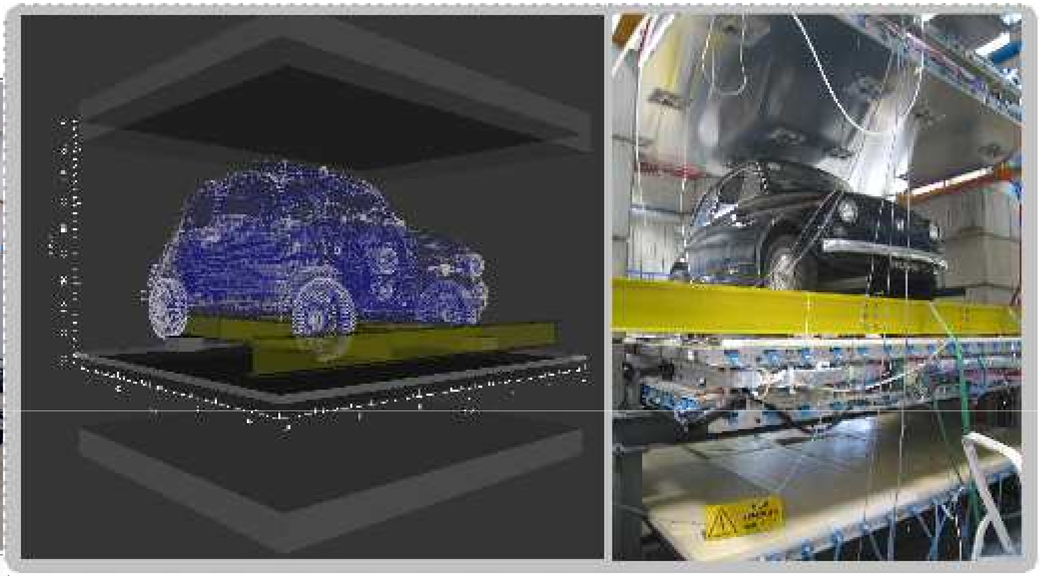




https://ec.europa.eu/research/industrial_technologies/pdf/rfcs/summaries-rfcs_en.pdf.

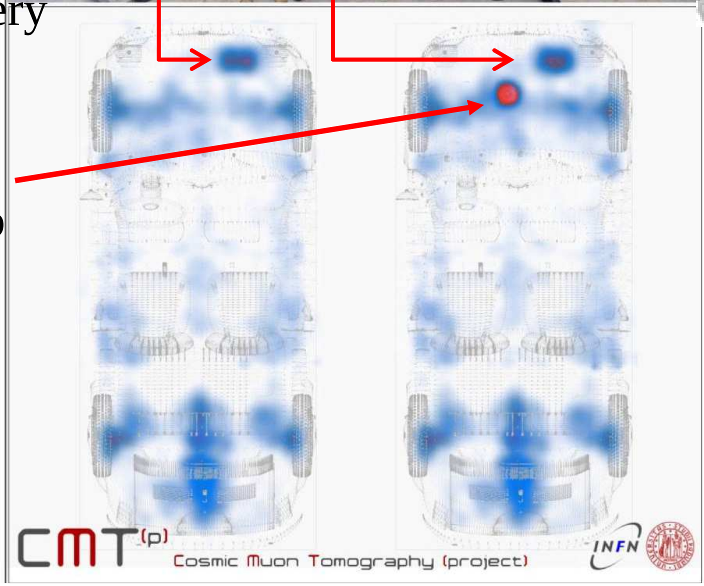
Cosmic Muon Tomography in transport control

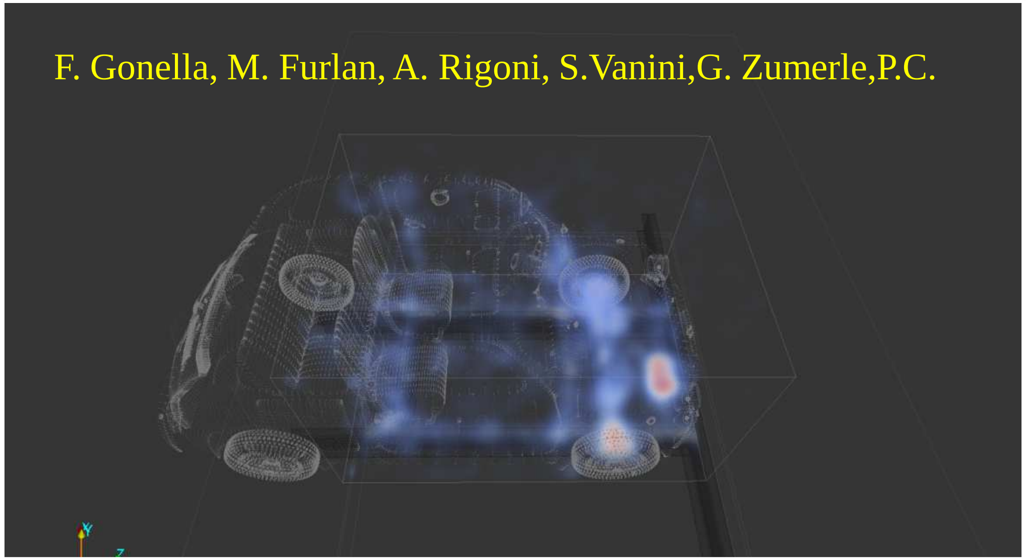
Other example: FIAT 500L on demonstrator



Battery

1l Pb





Industrial application

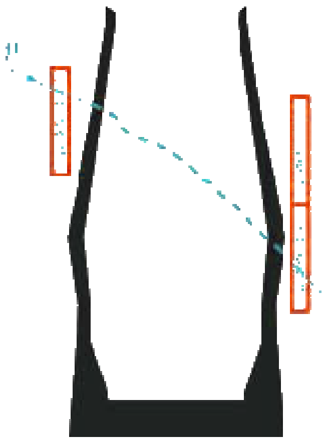
Cosmic Muon Tomography in Blast furnace control

Mu-Blast: European project to characterize the inner status of a Blast furnace (RFSR-CT-2014-00027)

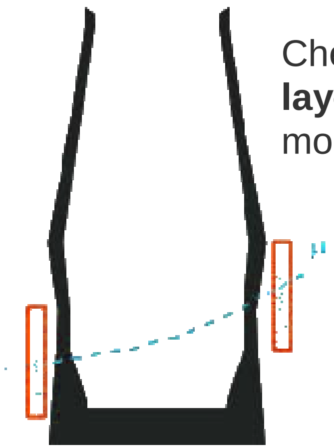
Research Fund for Coal & Steel

INFN · CSM · LKAB · swerea | MEFOS

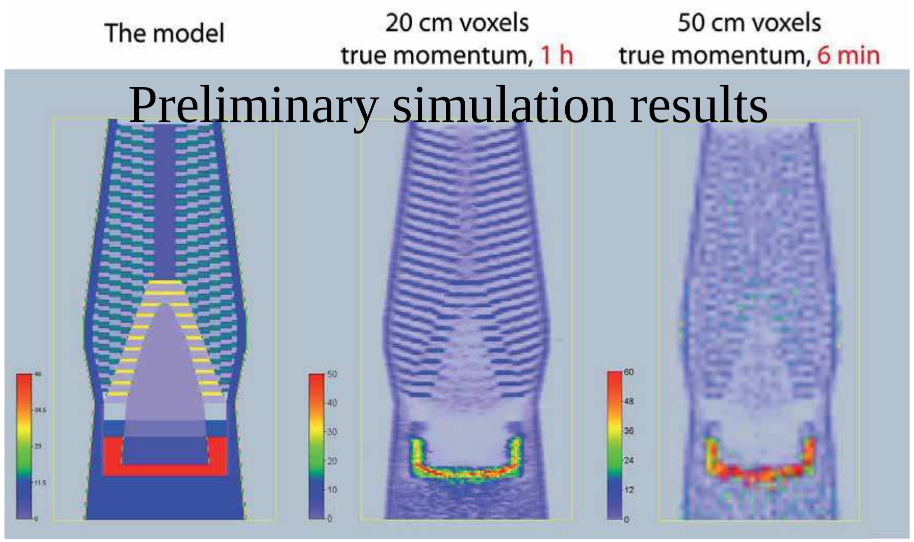
Blast furnace imaging



Monitor the density profile of the materials. The spatial distribution of the three main components (ore , coke and partially reduced metal) can be monitored profiting of their different densities.



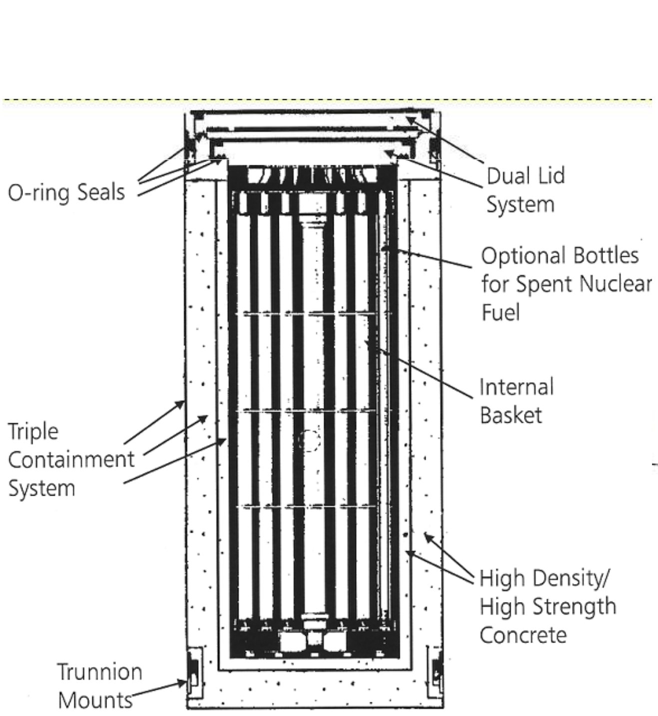
Check **the thickness of the BF internal layer in** the “heart”. This check allows to monitor the ageing status of the furnace

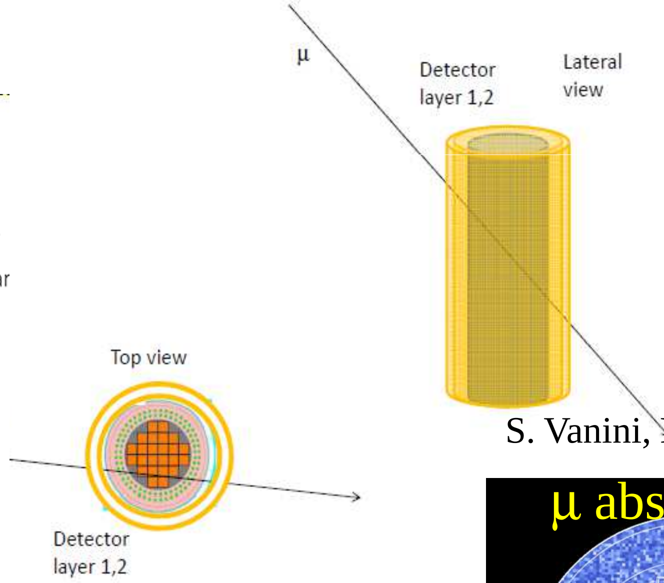


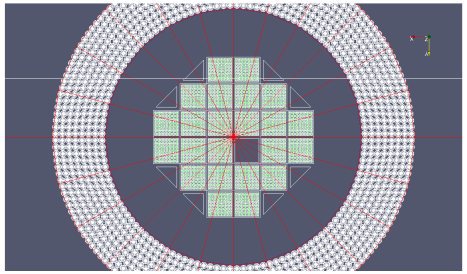
Spent nuclear fuel control*

No validated methods to verify the content of storage containers without opening
Possibilities: neutron radiography or muon radio/tomography.

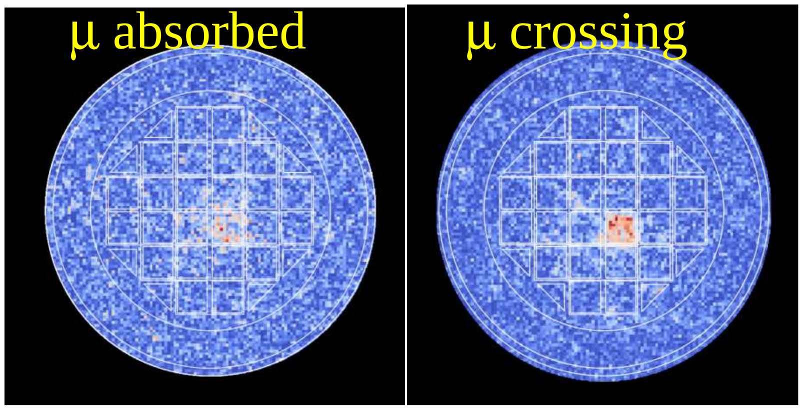
Detectors positioned around the container ⇒ Absorption, Transmission and MCS







S. Vanini, P. Peerani, A.Rigoni, G. Zumerle, P.C.



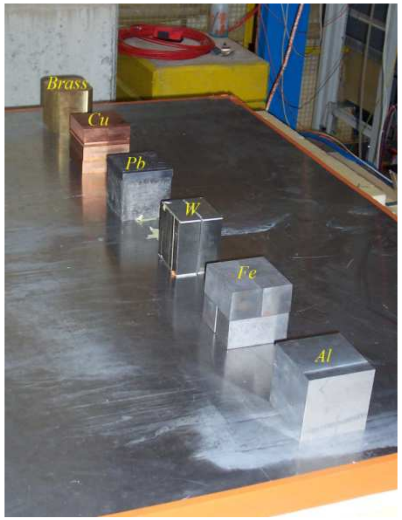
*A lot of activity: see reference list

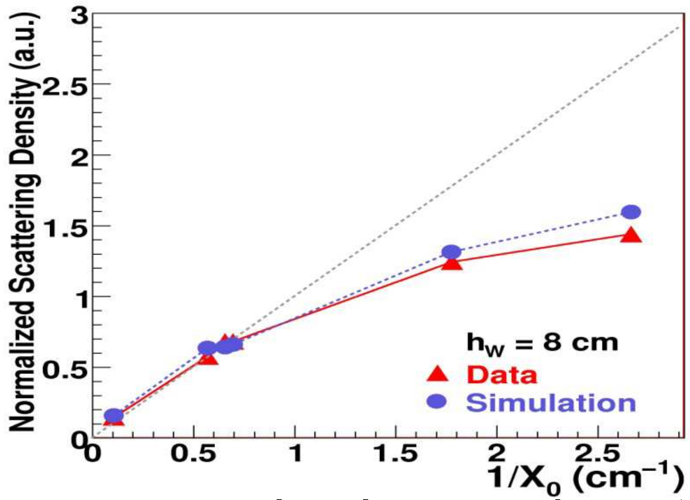
Precision measurements

- **Is it possible to make precision measurements with MCS tomography?**
- **Is it possible to determine LSD (or the ratio $R=\lambda/\rho$) of a material with an uncertainty≤ 10% ?**
- **Is it possible for a large LSD range?**

Several difficulties:

- **The choice of the parameter $<1/p^2>$ in absence of p measurement imply a careful calibration**
- **The muon spectrum is modified by the absorption of low energy muons then producing a saturation effect …..**





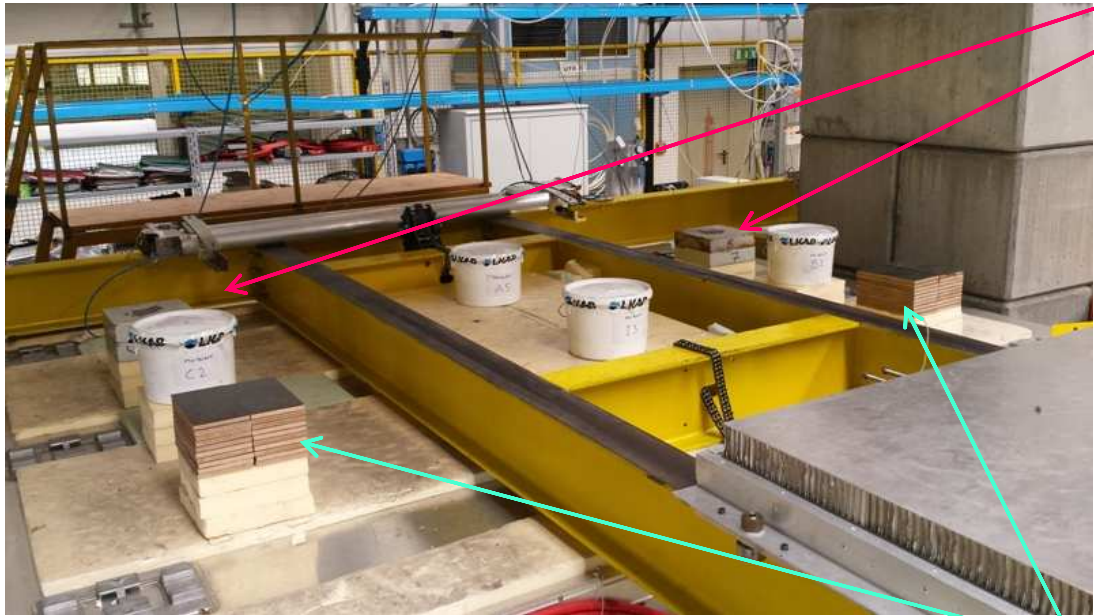
S. Pesente et al., Nucl. Instrum. Meth. **A 604 (2009) 738.**

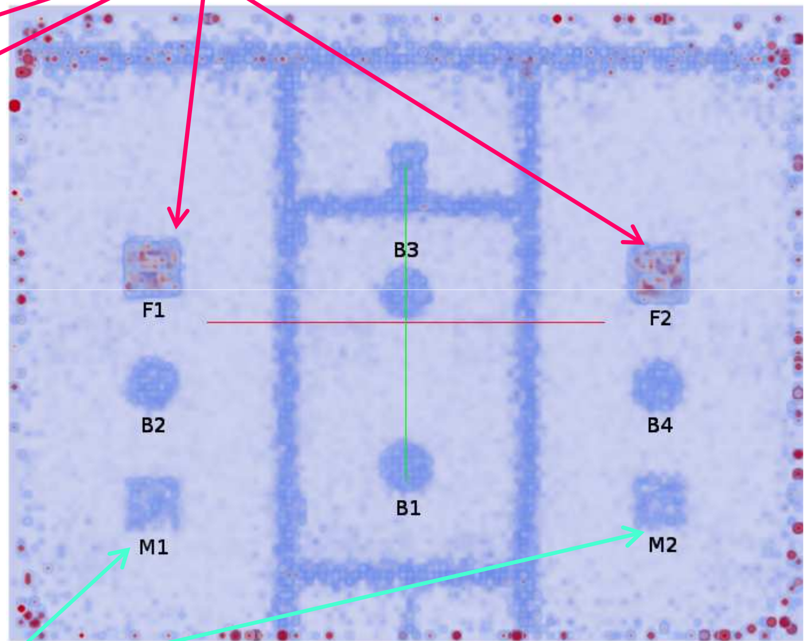
Precision measurements

Istituto Nazionale di Fisica Nucleare Sezione di Padova

Is it possible to make precision measurements with MCS tomography?

Iron blocks





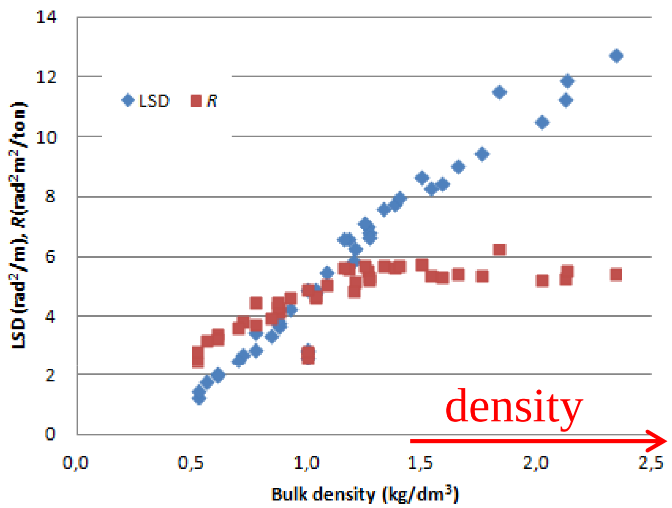
Despite several difficulties due to calibration and saturation effects...

Mock-up for normalization (with known LSD)

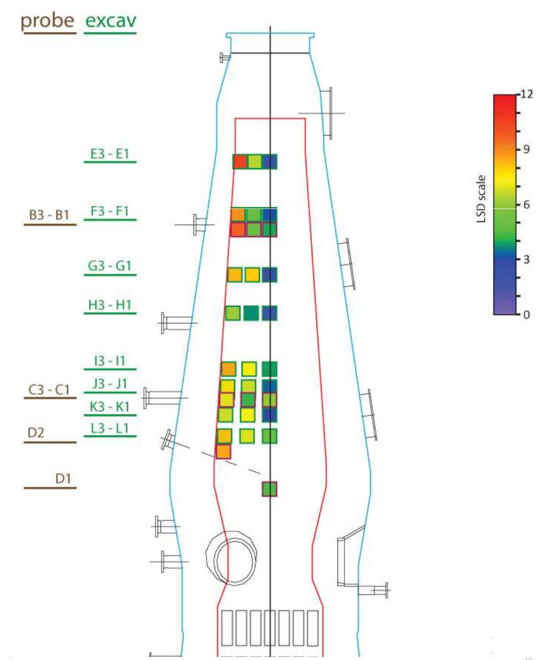
Precision measurements

an important output of Mu-Blast project*:

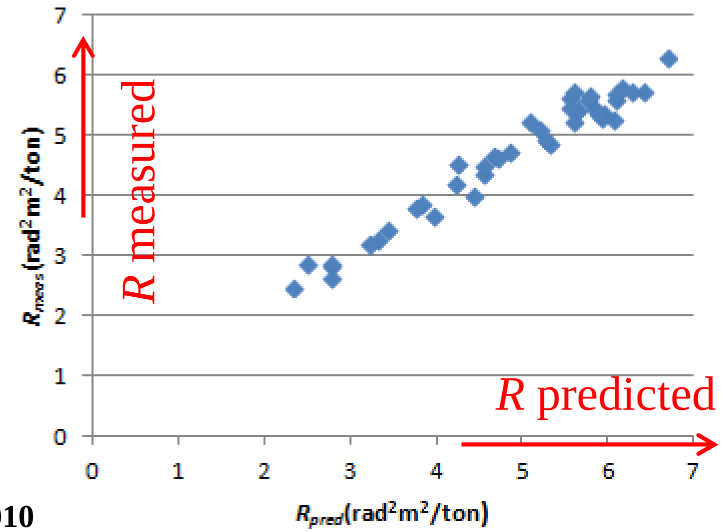
Yes!



Several materials collected from a furnace with a wide range of LSD or *R*



Good correspondence of measured *R* with predicted values



Expected precision 7-10%

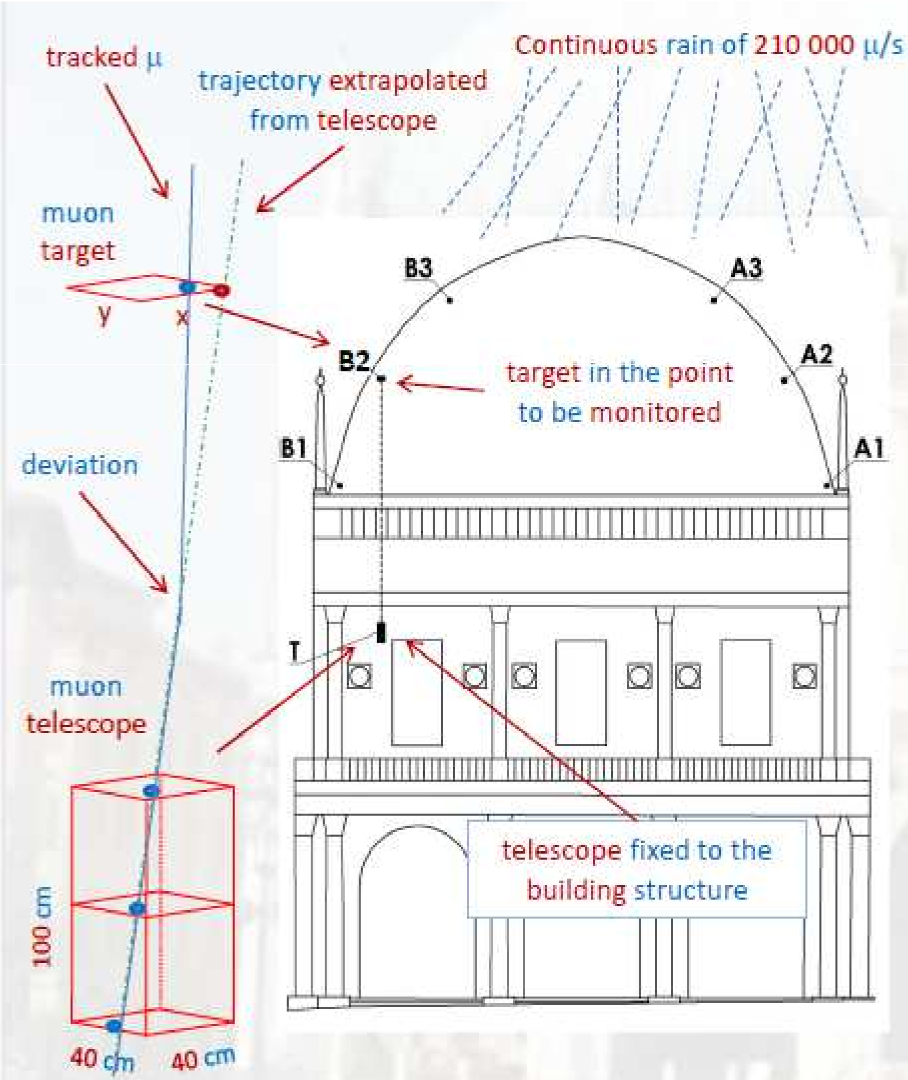
$\Delta R = R_{meas}/R_{pred} - 1$

Measured :
mean ΔR= -3.1%
with r.m.s. of 4.8%

*E. Åström et al., 2016 JINST **11 P07010**

Monitoring of building stability

Brescia Palazzo della Loggia*



Target displacement can be measured by statistical inference

Appealing features

- Use of a natural source of radiation
- μ are highly penetrating; walls and floors are easily traversed
- No need of visibility or empty spaces
- Limited invasiveness and flexibility
- Possibility to design a global monitoring system (one telescope more targets)

Limitations

- Stochastic nature of muon deviations in crossing matter
- Need to cumulate statistical distributions for application of statistical inference
- Low rate of cosmic ray radiation which implies long data takings
- unfit when promptness of response is needed

*Courtesy of A. Zenoni arXiv:1403.1709v1

Final remarks

The use of cosmic muons for applicative purposes is plenty of possibilities and the field is evolving quickly.

It is an important technological transfer from HEP and detector development to the society

From our point of view (HE Physicists) there are several technological, computational and analysis challenges that should move the interest to participate

Resources should arrive mainly from alternative funding subjects w.r.t. “standard” research agencies: this requires an effort to prepare and submit appropriate proposals for projects and to involve potential partners out of research/academic network.

New Ideas and more collaborators are welcome!


Thank you

Backup

Muon Tomography (in pills)

basic questions and corresponding answers

• What does CMT measure? (which kind of information about a material can be obtained from CMT?)

• The linear scattering density* (LSD) that is proportional to the material density $\lambda = \rho R$ where $R(Z_i, A_i, w_i)$ is function of the fraction by weight w_i of the i^{th} element with atomic number Z_i and mass number A_i. For a pure element: $\lambda \underset{\sim}{\propto} Z\rho$

• Which LSD should we expect for a composite material?

•We have: $R_c = \sum_i w_i R_i$
and consequently $\lambda_c = \rho_c R_c$

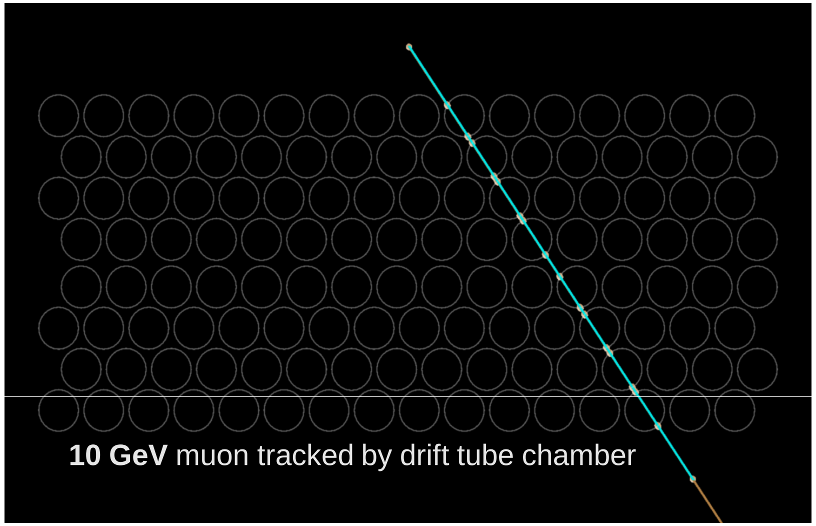
• What happens if analysed materials are available as a compound of pieces in air?

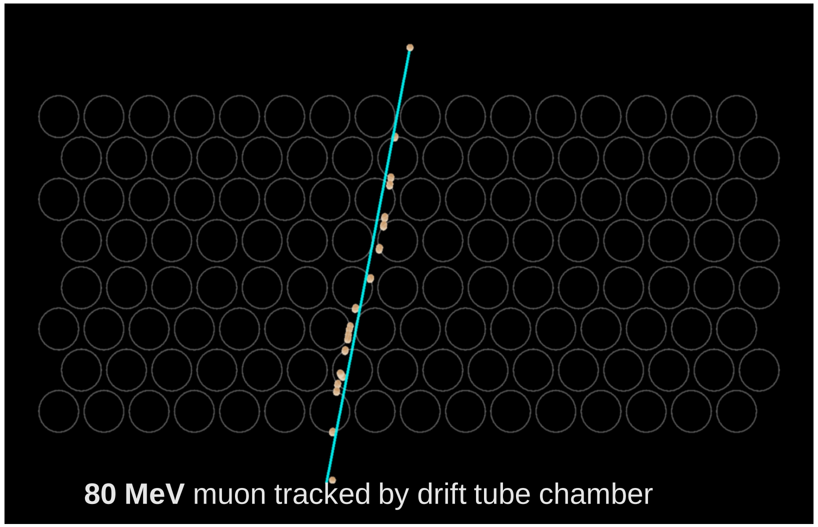
• Considering the bulk density, the LSD scales accordingly, so the ratio *R* is not affected.

* The LSD values are given in rad^2/m

Example of rough momentum estimation

Momentum Estimation from muon chamber track fit





References

[1]General/Pioneer.
E.P. George, *Commonwealth Engineer (1955) 455.*
L.W. Alvarez et al., *Science* ***167 (1970) 832.***
K. Nagamine, et al., Nucl. Instr. and Meth. A 356 (1995) 585.
K.N. Borozdin et al., Nature **422** ***(2003)*** 277.
L.J. Schultz, et al., Nucl. Instr. and Meth. A 519 (2004) 687.
L.J. Schultz, et al., IEEE Trans. Image Process. 16 (2007) 1985.

[2] Experimental MCS tomography
M. Benettoni et al., DOI: 10.1109/NSSMIC.2007.4437186
S. Pesente et al., Nucl. Instrum. Meth. **A 604 (2009) 738.**
L. Cuéllar et al., DOI: 10.1109/NSSMIC.2010.5873718
M. Benettoni et al., 2013 JINST **8 P12007**
J.Burns et al., 2015 JINST **10 P10041**
E. Åström et al., 2016 JINST **11 P07010**

[3] Detectors for Cosmic muon applications
http://mutomweb.pd.infn.it:5210/
https://www.decisionsciences.com/
K. Gnanvo, et al., **arXiv:1011.3231**
Xiaoguang Yue et al. Published in: Nuclear Science Symposium and Medical Imaging Conference (NSS/MIC), 2012 IEEE
P. Baesso et al., 2013 JINST **8 P08006.**
S. Riggi et al.,Journal of Physics: Conf. Series, 409 (2013), p. 012046
P. Baesso et al., 2014 JINST **9 C10041.**
J. Marteau et al., Measur.Sci.Tech. **25 (2014) 035101**
Shitao Xiang et al., DOI: 10.1109/RTC.2014.7097518
M. Biglietti, Published in **PoS TIPP2014 (2014) 290**
L. G. Dedenko et al., Bull.Lebedev Phys.Inst**. 41 (2014) no.8, 235-241**
Xuewu Wang et al., Nucl.Instrum.Meth**. A784 (2015) 390-393**
P.La Rocca et al., Nucl.Instrum.Meth**. A787 (2015) 236-239**
V. Anghel et al., Nucl. Instrum. Meth. **A 789 (2015) 12.**
A.Nishio et al., Phys.Procedia **80 (2015) 74-77**
A. B. Aleksandrov et al., Phys. Part. Nuclei Lett**. (2015) 12: 713.**
F. Riggi et al., EPJ Web Conf**. 117 (2016) 05003**
Dezső Varga et al., **arXiv:1607.08494**

4] Industrial applications
M. Furlan et al., *(ANIMMA), Marseille, France,*
23–27 June 2013, doi: 10.1109/ANIMMA.2013.6728043.
Musteel project , *Research Fund for Coal and Steel* RFSR-CT-2010-00033
https://ec.europa.eu/research/industrial_technologies/pdf/rfcs/summaries-rfcs_en.pdf.
Mublast project, *Research Fund for Coal and Steel* RFSR-CT-2014-00027, 655, available from:
https://ec.europa.eu/research/industrial_technologies/pdf/rfcs/summaries-rfcs_en.pdf.
J.M. Durham et al., AIP ADVANCES **5, 067111 (2015)**

[5]Spent nuclear fuel control
G.Gustafsson UU-NF 05#08 (October 2005) UPPSALA UNIVERSITY NEUTRON PHYSICS REPORT ISSN 1401-6269
G. Jonkmans et al. **arXiv:1210.1858**
A.Clarkson et al., Nucl.Instrum.Meth. **A746 (2014) 64-73**
A.Clarkson et al., Nucl.Instrum.Meth. **A745 (2014) 138-149**
A.Clarkson et al., JINST **10 (2015) no.03, P03020**
D. Poulson, et al**. arXiv:1604.08938v1**
S. Chatzidakis et al., Nucl.Instrum.Meth. **A828 (2016) 37-45**
S. Chatzidakis et al., **arXiv:1606.07567**

[6]Geological applications
H. K. M. Tanaka et al., Earth Planet. Sci. Lett. **306**, 156–162 (2011).
G, Ambrosi et al., Nucl.Instrum.Meth**. A628 (2011) 120-123**
J. Marteau et al., Nucl.Instrum.Meth**. A695 (2012) 23-28**
K. Jourde et al., **arXiv:1307.6758**
A. Anastasio et al., Nucl.Instrum.Meth. **A732 (2013) 423-426**
D. Carbone et al., Geophys.J.Int**. 196 (2014) 633-643**
J. Klinger et al., Int. Journal of Greenhouse Gas Control **42 (2015) 644-654**
J. Marteau et al**., arXiv:1510.05292v1**
S. Pal et al., **Springer Proc.Phys. 174 (2016) 479-485**
J. Marteau et al., **PoS PhotoDet2015 (2016) 004**
K. Jourde et al., **arXiv:1606.03003**

References

[7]Archeological applications

H. Gómez et al., AIP Conf. Proc. **1672, 140004 (2015)**

H. Gómez et al., J.Phys.Conf.Ser. **718 (2016) no.5, 052016**

[8] Survey of Nuclear plants

K.N. Borozdin et al., Phys.Rev.Lett. **109 (2012) 152501**

John Perry et al., J.Appl.Phys. **113, 184909 (2013)**

H. Fujii et al., PTEP 2013 **(2013) no.7, 073C01, arXiv:1305.3423**

[9]Algorithms, feasibility studies, simulations

K. Gnanvo, et al., DOI: 10.1109/NSSMIC.2008.4774639

Matthias Ihl : **arXiv:1008.1241**

V. Anghel et al., DOI: 10.1109/NSSMIC.2011.6154302

A. B. Aleksandrov et al., Bull.Lebedev Phys.Inst**. 39 (2012) 269-276**

C. Morris et al., **arXiv:1210.6102**

Baihui Yu et al., DOI: 10.1109/NSSMIC.2013.6829783

A. Zenoni et al., **arXiv:1403.1709v1**

S.Chen et al., JINST 9 (2014) **no.10, C10022**

D. Mitra et al., **arXiv:1412.6485**

K. Jourde et al., Geosci. Instrum. Method. Data Syst. Discuss., **5, 83-116, 2015**

A. Clarkson et al., JINST 10 (2015) **no.03, P03020**

M. Bandieramonte et al., J.Phys.Conf.Ser. **608 (2015) no.1, 012046**

K. Boniface et al., **arXiv:1605.01565**